Defense Technical Information Center Compilation Part Notice

This paper is a part of the following report:

- *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention. Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

- *To order the complete compilation report, use:* AD-A325 558

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

19971126 049

OFF-LINE AND ON-LINE MOTOR ELECTRICAL MONITORING AND CONDITION ANALYSIS: PAYOFFS AND PROBLEMS

Jack R. Nicholas, Jr.,
PdMA Corporation
2448 Holly Avenue, Suite 200
Annapolis, MD 21401-3148

Abstract: This paper provides insight into and describes motor electrical condition monitoring and analysis methods in use for decades and provides a comparison with state of the art methods developed and introduced in the 1990's. Nine methods for condition monitoring of motors are described. In particular, the technology generically called "motor circuit analysis" available from an increasing number of commercial sources (and now used in many different countries) is compared in a bala ;ed manner to three other off-line and five on-line test methods. Five techniques for analysis of motor electrical data from the nine technology methods are tabulated for comparison. A sixth, very powerful, analysis technique is discussed. Advantages and disadvantages of off-line and on-line methods are tabulated and tied to specific technologies where applicable. One case history involving two methods from a commercial activity is presented to illustrate a problem and a payoff. The difficulty of gaining acceptance of standards developed to support the analysis using newly introduced technologies is described. The status of industry consortiums established to set standards for new and refurbished motor purchases and for ensuring easy integration of data from any predictive technology used for monitoring of any machinery is briefly discussed.

Key words: Motor condition monitoring, motor circuit analysis, electrical predictive maintenance, motor diagnostics

INTRODUCTION: Motor electrical condition monitoring of a limited nature has been possible for decades using a number of qualitative and quantitative analysis methods. However, the process of arriving at a definitive, non-subjective conclusion regarding comprehensive motor electrical health has been difficult and time consuming until recent years. The availability of powerful, field portable computers has made it possible to quickly and definitively assess the major parameters which may be used to characterize condition. The computers, combined with an increasing number of software programs and small electronic packages for applying innovative measurement methods, enable technicians to quickly gather, store, recall, analyze and present the mass of data needed to perform electrical predictive maintenance and diagnosis.

This paper describes some of the most common "traditional" condition monitoring techniques, such as:
-resistance to ground (RTG) testing,
-surge comparison (Surge) testing,
-high potential (HiPot) testing,
-motor current balance analysis (MCBA).

It then contrasts those listed above to some newer methods, such as:
-motor circuit analysis (MCrA),
-motor current signature analysis (MCSA),
-motor power or electrical signature analysis (MPA),
-motor flux analysis (MFA),
-motor normalized temperature analysis (MNTA).

Payoffs using all of these methods are presented in the form of actual examples or results which may be reasonably expected based on the nature of the measurements taken. Problems most commonly encountered employing or interpreting data from the test methods are also described.

Analysis techniques used for each of the methods listed above are tabulated. Analysis techniques most commonly used in predictive condition monitoring include the following:
-trend analysis,
-pattern recognition,
-correlation analysis,
-tests against limits and ranges,
-relative comparisons,
-statistical analysis.

Correlation of data from various technologies can greatly strengthen a predictive maintenance program. This analysis technique can become much more widely used if vendors of predictive and diagnostic software adhere to "open architecture" and common communications and protocol standards being developed and discussed by an industry consortium which has been working on this subject for over a year.

Difficulty gaining acceptance by maintenance professionals of newer motor condition monitoring methods is described. Part of the difficulty comes from the fact that it takes a long time for organizations which set standards to reach consensus and publish criteria for employment of new monitoring methods. This is being overcome somewhat by individual and at least one group of companies which have established standards for purchase of motors. The standards require measurements based on the more advanced monitoring methods described in this paper.

CONDITION MONITORING METHODS: Following are descriptions of the condition monitoring methods listed above. It is recognized that other methods exist which have been proven useful in monitoring motor electrical conditions of various types. However, the methods selected for presentation in this paper are those which are commercially available and applicable to the broadest range of motor types and outputs.

-Resistance to Ground (RTG) Testing - As applied to motors, the most commonly used method of resistance to ground (RTG) testing measures the leakage current flowing to and through an insulation system to ground under the pressure of a controlled (known) electromotive force (voltage). The test result, in ohms, is derived by dividing the measured current into the known voltage. This relationship is known as Ohm's Law. National electrical codes, industrial and professional standards institutes and associations provide regulatory standard minimums for RTG values on circuits required to carry electric power. The condition being monitored is the integrity of the insulation system isolating the circuit from ground. For larger motor circuits, a variation of this test method involves calculation and analysis of ratios of RTG values taken seconds or minutes apart on the same motor circuit. These variations eliminate any need for temperature correction of RTG measurements and make apparent the combined effects of circuit capacitance and insulation polarization on total current flow caused by application of voltage to the circuit under test. Condition criteria exist for certain commonly used RTG ratios, such as polarization index (ratio of RTG after 10 minutes to RTG after 1 minute of continuously applied, constant voltage) and dielectric absorption ratio (RTG value taken at 1 minute divided by the RTG value taken after 30 seconds of continuously applied, constant voltage). Almost all maintenance electricians have conducted resistance to ground tests at some point in their careers. However, few know what is happening during the testing, which can be costly when readings approach minimum allowable values.

-Surge Comparison (Surge) Testing - Surge or surge comparison testing involves insertion of controlled electrical pulse(s) into a motor from (one or twin) capacitor or capacitor-like circuit(s). The return pulses, which have been "damped" and may exhibit instability caused by the effects of changing inductive reactance of the motor coils, are evaluated to assess the condition of winding coil turn-to-turn and ground insulation in all motors. Surge testing also reveals phase-to-phase insulation and coil orientation (erroneous connection) problems in polyphase motors. Evaluation is done using oscilloscope trace(s) of return pulse(s) created by effects of any variation in impedances of part(s) of the motor circuit on the inserted (DC) electrical pulses. Comparison is most often performed with simultaneously inserted pulses into polyphase motors. Modern surge testers include a computer for storage and later recall of oscilloscope traces of return pulses for comparison with those from the same circuits at widely separated times. This allows more reliable evaluation of changes in motor electrical condition to be performed by comparison of traces taken months or years apart on DC and single phase AC motor circuits. It also allows an analyst to subjectively evaluate health and degradation of polyphase motors over time. Many motor manufacturers use surge testing as a quality tool. Motor rewind shops use the method for diagnosing incoming motors. Many facilities use the technique for diagnosis, periodic testing and more recently as a predictive condition monitoring tool for motors and small generators.

-High Potential (HiPot) Testing - HiPot testing involves application of either AC or DC voltage higher in value than that for which a motor circuit is rated. The test is used to evaluate the integrity or margin of the ground insulation system against its breakdown under electromotive forces. Guideline evaluation criteria are available from various codes, standards and texts on maximum values to use in conducting the testing. Voltage is controlled by the test unit operator. Current flowing into the motor circuit and thence through and over the ground insulation system under test is measured and recorded. If no indication of insulation breakdown occurs at the maximum voltage established by the test criteria, the test is terminated and declared to be successful. Many motor rewind shops and facility maintenance teams use this method routinely.

-Motor Current Balance Analysis (MCBA) - For polyphase motors a simple set of two or three on line current measurements, their mathematical comparison and calculation of percentage unbalance is an excellent indication of motor condition. Unbalance usually results from impedance mismatch between phases of a motor circuit. Impedance changes occur because of motor winding degradation (turn-to-turn or phase -to-phase shorts) and/or the development of high resistance connections anywhere in the motor circuit from motor control center into the motor. Current unbalance can also be caused by voltage unbalance from the generation, transmission or distribution supply systems, although not as frequently. In the latter case, although the cause may be external, motor degradation and failure of one or more of its insulation systems will occur (due to overheating and accelerated aging) if the unbalance is not corrected.

-Motor Circuit Analysis (MCrA) - Motor circuit analysis (MCrA) involves measurement of four "natural" electrical parameters using closely controlled AC and DC input signals from a test unit. These are resistance in the conductor path, inductance, capacitance to ground and resistance to ground. Analysis involves combinations of these parameters, calculations of unbalance and graphical diagnosis. Results may be compared to well accepted standards (e.g., for RTG) or empirically derived guidelines.The guidelines are based on experience analyzing tens of thousands of motors. Motor predictive maintenance personnel can then quantitatively characterize motor circuit electrical conditions. This method is growing in popularity and is used internationally. The most advanced application of this test method indicates the following problems:

- Resistive unbalance in AC three phase motor circuits (causing overheating and premature and uneven stator winding failure)
- Excessive resistance in DC motor circuits (which may interfere with control)
- Inductive unbalance in AC three phase motor stators (indicating quantitatively the extent of shorted turns)
- Loss of inductance in AC synchronous or wound rotors (indicating quantitatively the extent of shorted turns)
- Loss of inductance in DC field or armature winding circuits (indicating quantitatively the extent of shorted turns)
- Presence of broken or cracked rotor bars or end rings and electrical or mechanical eccentricity
- DC armature shorts, opens or grounds (through quantitative and graphically presented

bar-to-bar readings and profiles)

- Temperature corrected and time consistent resistance to ground (RTG) conditions.
- Build up or presence of dirt or moisture on the outside of winding insulation systems (through correlation with capacitance to ground measurements over time)
- Polarization Index, Dielectric Absorption or other ratios from RTG readings

-Motor Current Signature Analysis (MCSA) -This method is known by several different commercial and generic names, many of which abbreviate to the same set of initials, MCSA. The most common applications involve analysis of two AC motor line current spectra. The first is in the frequency domain around the power supply line frequency (60Hz in North America, 50 Hz in most other parts of the world). The second is in the frequency domain around the center frequency calculated by multiplying the number of rotor bars or stator slots times the motor rotational frequency. Frequency spikes (sidebands) in the spectrum around the line frequency spike indicate the presence and influence on current amplitude of various faults in motors as well as dominant mechanical characteristics of both the motor and device(s) driven by it. A set of empirically derived numerical relationships between amplitudes of the line frequency and sideband frequencies indicate the severity of the problem being analyzed. Sidebands around the slot times rotational frequency and their relative amplitudes indicate the presence and relative severity of eccentricity problems. The most common faults detected (but not all distinguishable from each other) by MCSA are:

- Broken or cracked rotor bars
- High resistance joints in rotor bars or wound rotor conductors
- Broken or cracked end rings in squirrel cage rotors
- Casting porosity affecting current flow in die cast rotors
- Static and dynamic eccentricity conditions between rotor and stator
- Mechanical defects associated with the rotating element (e.g., bearing degradation)

-Motor Power (or Electrical Signature) Analysis (MPA) - This method involves measurement, conditioning, instantaneous recording and further processing for analysis in time and frequency domains of all phase currents and voltages associated with a motor. From the analysis and various easily performed calculations, power factor, real, reactive and apparent power can be derived, tabulated and graphically presented. Instantaneous variations of these and the basic, measured values in each phase, one phase compared to the others and power in the overall circuit may be used to assess conditions of the motor, the power system supplying and controlling it and the device(s) driven by it. Power or electrical signature analysis provides a potentially huge amount of data and opportunities to detect degraded conditions at very early stages of their development. The method has been used to monitor not only for motor defects but also for analysis of mechanical performance of valves, pumps, couplings and other devices being driven by or through them. Full capabilities have yet to be realized due to the fact that the MPA method has gotten attention only in the past few years. Most of that attention has been in the nuclear utility industry, which has some limitations on extent to which relatively new methods can be applied.

-Motor Flux or Leakage Flux Analysis (MFA) - Magnetic flux created by currents in motors is concentrated largely inside the enclosure or shell. However, some of the magnetic field may be detected in the space near the outside of most motors. This "leakage flux" varies with conditions found inside the motor and the condition of power supplied to it. Over the years, various investigations have resulted in some correlation between trended variations in the leakage flux field and defects such as broken rotor bars and stator turn-to-turn or phase-to-phase shorts. Analysis involves comparison of conditioned output signals of a flux detection coil consistently mounted external to the motor. The signals are presented on a Fast Fourier Transformed frequency spectrum which typically runs from 0 Hertz to 10 or 20 Hertz above two times the line frequency. Specific frequency lines in the spectrum of flux amplitudes can be related to particular types of defects. As the amplitude of a particular line increases, it indicates that the condition identified as related to it is growing worse. Sideband analysis similar to that described in motor current signature analysis is also used, although there is no direct correlation established (or revealed) yet between the numbers used in each method.

-Motor Normalized Temperature Analysis (MNTA) - Most motor defects are accompanied at some point in their development with increased temperature. In applying MNTA, temperatures are taken at specific points, such as on the outside of an end bell closest to where a bearing is located, an outlet air vent or the outer skin of the casing. The measured temperatures must be "normalized" to account for load and ambient conditions and are trended over time. Increasing trends may indicate the onset of degradation. Effects of location relative to direct sunlight, of design (such as outer skin thickness and material used, internal airflow patterns, frame design, etc.,), and surface paint color must all be accounted for or mitigated. Many critical motors are equipped by the manufacturer with temperature sensors at key locations, making the application of this method of motor condition monitoring redundant. However, there are many critical motors without this capability which are candidates for monitoring with relatively low cost, hand held temperature measurement devices. Typical conditions manifested by increased temperatures in motors include:

- Degrading bearings
- Rotor faults (broken or cracked bars and end rings)
- Clogged ventilation filters or screens
- Stator winding faults (turn-to-turn and phase-to-phase)
- Couplings which are misaligned or need lubrication
- Unbalanced currents which are caused by high resistance in the motor circuit

PAYOFFS: Each of the methods described above provides either a subjective (non-quantitative) or objective (quantitative) measure of condition of motors. Some provide much more, indicating condition of the entire motor circuit, the power supplied to the circuit, condition of the motor drive in the circuit and in some cases the condition of the device being driven. The payoff is the capability to assess condition(s) before actual failure. This allows orderly planning and repair or replacement to occur at minimum overall cost, including the cost of lost production, which is often the dominant factor in the payoff total. Table 1 summarizes the way (subjective and objective) conditions detectable from the methods described in this paper are characterized.

Table 1. Motor Electrical Condition Monitoring Capabilities of Various Methods

Condition Monitored O=Objectively S=Subjectively

Method	Insulation System Integrity	Contam-ination	Coils/ Wind-ings	Sq. Cage Rotor	Armature & Sync Rotor	Circuit and/or Drive	Bearings and Coupling	Driven End
RTG	O	O						
SURGE	S		S		S			
HiPot	O							
MCrA	O	O	O	O	O	O		
MCBA			O			O		
MCSA				O				O
MPA			O	O		O	O	O
MFA			O	O		O		
MNTA		O	O	O			O	

Motor circuit analysis, an off-line method, has the capability to monitor 6 of the 8 categories in the table. Motor power analysis, an on-line method, has the capability to monitor 5 of the 8 categories, including the two not monitored by motor circuit analysis. If both were applied to the same motor driven system, they would appear from the table to have combined capabilities to provide the most comprehensive condition data upon which to base overall assessments. No other combination of methods covers all of the categories tabulated. However, within each column of Table 1., the presence of an entry for a method (O or S) indicates a possibility of correlation of its data with the data from any other method which has an entry in the same column.

Correlation of data from predictive condition monitoring methods, such as vibration analysis, infra red thermography and wear particle analysis, with the methods described in this paper is strongly recommended and easily accomplished. Use of the correlation technique pays off in greatly strengthened predictive analysis conclusions and more compelling reports. Further discussion on this subject may be found in references 1 and 5 of the bibliography at the end of this paper.

Other analysis techniques, besides correlation, are used to assess present and predict future conditions in motor driven systems. Table 2. summarizes the techniques used for each method covered in this paper.

As illustrated in Table 2., only motor circuit analysis and motor power analysis provide data of sufficient quantity and variety to permit application of all five predictive analysis methods. This is another reason for selecting this combination of motor, predictive condition monitoring methods.

Table 2. Analysis Techniques Used On Data from Various Motor Electrical Monitoring Methods

Analysis Technique

Method	Trend Analysis	Pattern Recognition	Relative Comparison	Test Against Limit or Range	Statistical Analysis Technique
RTG	X			X	
SURGE		X	X	X	
HiPot				X	
MCrA	X	X	X	X	X
MCBA	X		X		
MCSA	X	X	X		
MPA	X	X	X	X	X
MFA	X	X	X		
MNTA	X	X	X		

PROBLEMS: Problems may be encountered in application of any condition monitoring method. Two particular problems concerning resistance to ground readings are managed effectively by one version of MCrA technology. They are consistent temperature correction and control of the time of measurement after application of the DC ground test voltage. These two criteria become very important when ground readings in circuits are approaching marginal conditions.

In a 1994 incident, excessive voltage was applied to 220 run out table motors in steel plant hot rolling mill. To determine if any were damaged as a result of the incident, it was decided that a "quick" check of resistance-to-ground (RTG) readings on these DC motor circuits was prudent. Electricians were dispatched with hand cranked and battery powered meters to take the readings as fast as possible. Readings taken indicated 138 out of 220 motors below acceptable values. The mill had only 10 spares available at the time. After questioning the results, the hot mill electrical foreman realized that the electricians had recorded the RTG readings without considering the time factor. RTG readings must be taken consistently at the same instant after application of the test voltage. Otherwise, circuit capacitive and polarizing influences will not be accounted for equally. Readings taken without consideration of the time factor are not repeatable nor comparable. The foreman ordered the tests redone using the motor circuit analysis methodology and equipment. Because of the accuracy of the time controlled method, he was also able to lower the RTG acceptance values used for the plant. Results of the retests indicated only five motors had RTG readings low enough to need replacement under the revised standards. The accuracy and repeatability of the time controlled RTG test method allowed reliance on RTG readings closer to the alarm value where these motors were determined to be unacceptable for continued service.

Fifteen other run out table motors in the retest (which provided all four motor circuit analysis parameters described in this paper) were found to have high conductor path resistance. Most of these problems were located in the DC power connection plug at the motor and were corrected and confirmed to be fixed during testing. High conductor path resistance conditions, which could affect control of the motor speed, are not detectable with an RTG test.

Other problems with individual methods relate to perceptions and actual statements in authoritative documents which imply that use of certain methods such as Surge and HiPot may damage motors. In spite of compelling test results and arguments by users and condition monitoring vendors to the contrary, the perceptions persist.

Another way of looking at the nature of the problems is to review advantages and disadvantages of off-line and on-line methods. The first four methods listed in the above tables are all off-line methods. The last five are all on-line. Table 3 summarizes advantages and disadvantages.

TABLE 3. Advantages and Disadvantages of Off-line and On-line Motor Condition Monitoring Methods

	Off-line Monitoring	**On-line Monitoring**
Advantages	1. Active, known and controlled test signals used. 2. Fewer extraneous signals on de-energized motor circuits to mask test results.	1. Passive - No test signals needed. 2. Monitoring can be done without interfering with production. 3. Hookup and/or data collection may be achieved for some methods and installations without special electrical safety considerations (MFA, MNTA).
Disadvantages	1. Motor must be shut down to perform testing, which may interfere with production. 2. Circuit must be proven safely deenergized before hookup of ALL off-line methods. 3. Test signals used are not always the same for different vendors. 4. Residual magnetism may influence some results (MCrA)	1. Many normal conditions provide test indications which mask fault. indications (MCSA, MPA, MFA). 2. Test hookup may be difficult to achieve safely without motor shutdown at some installations for some on-line methods (MCBA, MCSA, MPA). 3. Local conditions may influence test results (MNTA).

CONDITION MONITORING STANDARDS: Organizations which establish standards are typically slow to take up the subject of new monitoring methods. In the eyes of some potential users, the lack of national or international criteria for acceptance or rejection of motors based on condition data from new monitoring methods is justification for not applying them.

At least one ad hoc group of companies which buy large numbers of new and rebuilt motors each year has established acceptance criteria derived from motor circuit analysis experience for their purchasing agents to use. Criteria such as resistive and inductive unbalance are included in the consensus standards. Motor vendors were slow to accept these new requirements at first but have started to respond positively after threat of disqualification from bidding was raised by buyers.

Another ad hoc industry group, The Machinery Information Management Open Systems Alliance (MIMOSA), has begun an effort to develop conventions to achieve cost effective data exchange between dissimilar condition assessment, maintenance information and process control systems. The alliance teams are providing recommendations which will allow connecting proven, but fragmented, asset management technologies into high value, comprehensive providers of essential information. Such efforts will greatly aid establishment of central data bases and enable correlation analysis to be applied more easily, among many other benefits.

BIBLIOGRAPHY:

1. J. Flude and J. Nicholas, Predictive Maintenance Primer, April 1991, Electric Power Research Institute Nuclear Maintenance Applications Center, Palo Alto, CA.
2. J. Nicholas, Motor Electrical Predictive Maintenance and Testing, 1995/96 Edition, PdMA Corporation, Tampa, FL.
3. J. Nicholas, "Evaluating Motor Circuits", Maintenance Technology Magazine, November 1992, Chicago, IL.
4. J. Nicholas, "Predictive Maintenance of DC Motors", P/PM Technology Magazine October 1993, Minden, NV.
5. J. Nicholas, "Predictive Condition Monitoring of Electric Motors", P/PM Technology Magazine, August 1993, Minden, NV
6. J. Nicholas, "Motor Circuit and Motor Current Analysis", AIPE Facilities Magazine, July/August 1994, Cincinnati, OH.
7. B. Roberts, "Power Signature Analysis for Motor Driven Device Monitoring and Diagnosis", Duke Power Company, Huntersville, NC.
8. G. Lang, "Of Cages, Induction, Deduction, Bars, Vars and Squirrels" Sound and Vibration Magazine, December 1994.
9. S. Bowers and K. Piety, "Proactive Motor Monitoring" Maintenance Technology Magazine, June 1995, Chicago, IL
10. D. Brooks, V. Morgan, J. Nicholas, "Motor Analysis at Dofasco" Paper presented at the Conference on Advanced Technologies for the Steel Industry, October 1995, Cleveland, OH.